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16. ABSTRACT

Cotton (Gossypium hirsutum L. cv. 'SJ-2'), grown in open-top chambers in the Central Valley of California, was exposed to 6 ozone (O_3) treatments ranging from charcoal-filtered (CF) to ambient plus 0.10 ppm O_3 (1981) or twice ambient O_3 concentrations (1982) for the entire growing seasons of 1981 and 1982. Half the plots were irrigated optimally and the other half were water-stressed by providing 25% (1981) or 20% (1982) less irrigation water. During the typically hot, dry growing season of 1981 cotton yield in normally irrigated (NI) treatments was reduced 20% in non-filtered (NF) chambers relative to CF controls. Doubling ambient O_3 concentration reduced yield 45%. Water-stressed (WS) plants showed almost no response to O_3. In 1982, potential evapotranspiration during the growing season averaged 20% less and ambient O_3 concentrations averaged 39% lower than in 1981. Under these growing conditions, cotton yields in NI and WS treatments responded similarly to O_3. Yields in NF chambers were reduced 15% relative to CF chambers. Doubling ambient O_3 concentrations reduced yields 65%. The greater relative response of cotton to O_3 in 1982 may have resulted from the cooler more humid growing conditions, which increased the susceptibility of cotton to O_3.

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Cotton Yield Responses to Ozone as Mediated by Soil Moisture and Evapotranspiration[1]

PATRICK J. TEMPLE, O. CLIFTON TAYLOR, AND LAWRENCE F. BENOIT[2]

ABSTRACT

A 2-yr field study was conducted to determine injury and yield responses of normally irrigated and water-stressed cotton (*Gossypium hirsutum* L.) to a gradient of ozone (O_3) concentrations. Cotton (cv. SJ-2), grown in open-top chambers in the Central Valley of California, was exposed to six O_3 treatments ranging from charcoal-filtered (CF) to ambient plus 0.10 μL L^{-1} O_3 (1981) or twice ambient O_3 concentrations (1982) for the growing seasons of 1981 and 1982. Half the plots were irrigated optimally and the other half were provided with 25% (1981) or 20% (1982) less irrigation water (water-stressed treatment). During the typically hot, dry growing season of 1981, cotton yield in normally irrigated treatments was reduced 20% by ambient levels of O_3 in nonfiltered chambers (NF) relative to CF controls. Doubling ambient O_3 concentration reduced yield 45%. Water-stressed plants showed almost no response to O_3. In 1982, the weather was cooler and cloudier than normal and potential evapotranspiration during the growing season averaged 20% less and ambient O_3 concentrations averaged 39% lower than in 1981. Under these conditions, cotton yields at both levels of soil moisture treatments responded similarly to O_3. Yields in NF chambers were reduced 15% relative to CF chambers. Doubling ambient O_3 concentrations reduced yields 65%. The greater relative response of cotton to O_3 in 1982 may have resulted from the cooler, more humid growing conditions, which increased the susceptibility of cotton to O_3.

Additional Index Words: **air pollution, dose-response functions, water stress, *Gossypium hirsutum* L, herbicides.**

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Cotton (*Gossypium hirsutum* L.) is one of the major agricultural commodities of the USA and is the leading (legal) field crop in California (CDFA, 1983). Greenhouse (Oshima et al., 1979) and field experiments (Brewer & Ferry, 1974) showed that growth and yield of cotton can be reduced by chronic exposures to ozone (O_3). However, dose-response relationships between O_3 concentrations and yield of field-grown cotton have not been developed.

Plant water status as affected by soil moisture, relative humidity, and evapotranspiration can strongly influence responses of plants to O_3 (Macdowall et al., 1964; Otto & Daines, 1969; Heck, 1968; Rich & Turner, 1972; Ting & Dugger, 1968). Conditions conducive to open stomata and active gas exchange, such as high relative humidity and adequate soil moisture, increased uptake of O_3 and development of foliar injury symptoms (Otto & Daines, 1969; McLaughlin & Taylor, 1981). However, stomatal responses to evapotranspiration are complex (Hall et al., 1976; Cowan, 1977; Farquhar & Sharkey, 1982), and plant responses to O_3 as influenced by soil moisture and evapotranspiration have not been adequately studied in the field. The objectives of this study were (i) to develop dose-response relationships between yield of field-grown cotton and seasonal doses of O_3 at concentrations below and above ambient levels; and (ii) to determine how these dose-response relationships were influenced by soil moisture and evapotranspiration.

Experiments were conducted as part of the National Crop Loss Assessment Network (NCLAN) (Heck et al., 1982). The ultimate objective of NCLAN is to provide a national economic assessment of the impacts of air pollutants on agricultural productivity.

MATERIALS AND METHODS

Experimental plots were located at the USDA Cotton Research Station, Shafter, CA. The soil is a deep Wasco sandy loam (coarse-loamy, mixed nonacid, Thermic Torriorthent) with some variation in percent sand. Composite soil samples taken at depths of 0 to 30 cm and 30 to 60 cm from 20 locations within the field were analyzed for pH, conductivity, N, P, and K. All parameters were within the optimum range for cotton production and showed no significant plot-to-plot variation.

Preemergence herbicide (Treflan® [*a,a,a*-trifluoro-2,6-dinitro-*N,N*-dipropyl-*p*-toluidine], 0.6 kg ha^{-1}) was applied in April; the field was bedded up on 102-cm row spacings and preirrigated to field capacity to a depth of [illegible] cm. Cotton seed (cv. Acala SJ-2) was planted on 6 Apr. 1981 and on 21 Apr. 1982. After emergence, the site was mechanically cultivated and side-dressed with the standard fertilizer application of 67 kg ha^{-1} of 21–10–10 (N–P–K). Thirty plots were marked off on 7.6-m centers, 10 in each of three strips oriented east-west. Each plot contained six rows of cotton 6.1 m long. Plants were hand thinned to 7- to 10-cm spacing (an average of 13 plants m^{-1}) for an estimated density of 73 000 plants ha^{-1} in 1981 and to 12 plants m^{-1} in 1982 for an estimated density of 53 000 plants ha^{-1}. Altosid® [isopropyl (2E-4E) 11-methoxy-37, 11-trimethyl-2,4-dodecadienolate] (1.3 mL L^{-1}) was used to control aphids (*Aphis* spp.), and white fly (*Trialeurodes* sp.) through the season; Kelthane® (4,4′-dichloro-α-trichloro-methylbenzhydrol) (1.3 mL L^{-1}) was used to control mites (*Tetranychus* spp.), and Thuricide® (*Bacillus thuriginensis* Berliner) (1.1 mL L^{-1}) was used for lepidopteran larvae (*Spodoptera* spp.) control.

Twenty-four cylindrical open-top chambers (Heagle et al., 1973) 3 m in diam and 2.4 m high were centered on randomly selected plots. Chambers were equipped with frustra that restricted top openings to 1.94 m. Four additional plots were selected as ambient air (non-chamber) controls. Chambers were positioned over two center sample rows, leaving two guard rows inside each chamber. The fifth row from the north in each plot was designated as the companion row. Chambers were installed and blowers started on 8–10 June 1981 and 2 June 1982. Blowers were operated from 0600 to 2100 h, daily.

The 24 chambers were assigned at random to six levels of O_3 with four replications each. Ozone treatments in 1981 were (i) full charcoal filtration (CF); (ii) half-filtered (NF × 0.5); (iii) no filtration of ambient O_3 (NF); (iv) NF + 0.03 μL L^{-1} O_3; (v) NF + 0.06 μL L^{-1} O_3; and (vi) NF + 0.10 μL L^{-1} O_3.[3] In 1982, non-O_3 added treatments were the same as 1981, but O_3 was added in proportion to ambient O_3 concentrations to give ambient (NF) plus ½ of ambient (NF × 1.3); ambient + ⅔ (NF × 1.7), and double ambient concentration (NF ×

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[2] Assistant research botanist, professor of plant science, and post-graduate research associate, respectively.

[3] Note: 1 μL L^{-1} of O_3 = 1997 $\mu g/m^3$ at 20°C.

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2.0). Concentrations in O_3-added chambers in 1982 were controlled by an inline electronic signal controller directed by millivolt output from a Dasibi ozone analyzer (Model 1003-AH; Dasibi Environmental Corp., Glendale, CA) monitoring ambient O_3 at canopy height in an open (AA) plot. The controller signaled the Griffin O_3 generator (Model GTC-1A; Griffin Technics Corp., Lodi, NJ) to modulate voltage, hence O_3 output, in response to ambient concentrations. Ozone flow to each chamber was proportioned through flow meters (Model FM 112-02; Aalborg Corp., Monsey, NY). Ozone additions began whenever ambient concentrations exceeded 0.03 $\mu L\ L^{-1}$. In 1981, O_3 was added from 0900 to 1600 h PST 5 d $week^{-1}$, from 6 July, when plants were in the first bloom stage, to 15 September. In 1982, O_3 additions began on 2 June, when plants were at the two to three true leaf stage and 20 to 30 cm in height, and continued daily until 9 September.

Ambient, chamber, and AA O_3 concentrations were monitored from 16 June to 5 Oct. 1981 and from 2 June to 19 Oct. 1982. Ambient SO_2 was monitored with a Monitor Labs SO_2 Analyzer (Model 8850; Monitor Labs, Inc., San Diego, CA). Sample air from chambers and plots was collected 10 cm above canopy height through continuously aspirated dust-filtered Teflon® lines 45.7 m long. The lines merged at dual 12-port rotary sample valves (Scanivalve Corp., San Diego, CA) that rotated to the next position every 2 min so that every line was sampled for an average of 5 min h^{-1}. All standard NCLAN quality assurance protocols regarding calibration of instrumentation and line loss checks were followed at the prescribed intervals (Heck et al., 1984).

Plots were assigned at random to treatments designed to provide normal irrigation (NI) or water-stressed (WS) conditions. Each plot was individually diked and furrow-irrigated through a polyvinyl chloride (PVC) manifold system that delivered 25.4 mm of water per hour to each furrow. Irrigation scheduling was based primarily on leaf xylem water potential (ψ_l) (Grimes & Yamada, 1982). Pressure bomb measurements (Plant Water Status Console, Model 3000; Soil Moisture Equipment Corp., Santa Barbara, CA) were taken on uppermost ¾ to fully expanded leaves from one to three nonsample plants in each chamber or plot. All measurements were made within 3 h of solar noon near the end of the 8- to 10-d irrigation cycle. In 1981, WS plants were irrigated when ψ_l in those plots averaged −2.1 MPa; NI plants were irrigated at ψ_l = −1.8 MPa. In 1982, WS plants were irrigated when ψ_l reached −2.0 MPa; NI plants were watered at −1.8 MPa. Total seasonal irrigation averaged 63.9 ± 3.8 cm in NI plots in 1981; irrigation in WS plots averaged 50.1 ± 3.2 cm. In 1982, seasonal irrigation in NI and WS plots averaged 69.4 ± 2.8 cm and 55.6 ± 2.3 cm, respectively.

Visible symptoms of foliar injury were assessed on 10 Aug. 1981 and on 19–24 Aug. 1982. Percent of O_3-induced foliar injury was estimated in increments of 10% on four plants for each chamber or plot. Premature foliar abscission was counted as 100% injury.

Sample rows from chambers, open plots, and companion plots were harvested on 10–13 Oct. 1981 and 20–21 Oct. 1982. In 1981, bolls were harvested from 2.7 m from the centers of the two sample rows. In 1982, open bolls were collected from four separate 1-m sections of two center rows of each chamber or AA plot. Companion rows were sampled by harvesting four separate 1-m sections from each row. Data were also collected on number of open and green bolls and number of plants in each sample. A second pick 3 weeks later added very few additional mature bolls. First and second picks were combined and ginned at 5.5% moisture on a portable (Ten-Saw®) gin. In 1981, samples within chambers were combined before ginning; in 1982, the samples within chambers were analyzed individually. Pre-gin bulk weight and lint and seed weights were recorded for each sample. Fiber quality was analyzed at the USDA Cotton Research Station, Shafter, and classification was performed at the USDA Cotton Marketing Service, Bakersfield, CA.

Harvest data were analyzed in a completely randomized split-plot design with O_3 and irrigation as main plots and position in chamber as subplot factors. Companion plot data were analyzed for systematic trends across the field, but none were found. Analysis of covariance using companion plot data did not improve goodness-of-fit of regression models, so these data were not included in the final analysis. Dose-response equations were fit to individual chamber harvest data and seasonal 7-h O_3 concentrations by multiple regression analysis using linear, polynomial, and exponential models.

Daily meteorological data were obtained from a meteorological station located 300 m northeast of the field plots. Data on potential evapotranspiration were obtained from a Class A pan evaporator at the same location.

RESULTS

Air Quality and Meteorology

Growing conditions in 1982 were unusually cool and humid for the Central Valley of California, particularly in comparison with 1981. Accumulated degree days above 15.5°C totaled 2713 during the 1981 growing season and 2267 in 1982, a reduction of 20%. Monthly average pan evaporation was also 20% lower in 1982, particularly during June, July, and August (Table 1). These atypical growing conditions in 1982 influenced crop development. Boll set was unusually early, and the first 4 weeks of flowering produced 93% of final yield, compared with 58% historically (Kirby, 1982). Plot yields in 1982 were about the same as in 1981, and yields on experimental AA plots were similar to those obtained at the USDA Cotton Research Station.

Ozone concentrations were lower in 1982 than in 1981. Seasonal 7-h (0900–1600 h PST) mean ambient O_3 concentration in 1982 was 0.047 $\mu L\ L^{-1}$. In 1981, seasonal 7-h mean ambient O_3 concentration was 0.077 $\mu L\ L^{-1}$. Seasonal 7-h O_3 means for chamber treatments in 1981 were CF = 0.018 $\mu L\ L^{-1}$; NF × 0.5 = 0.045 $\mu L\ L^{-1}$; NF = 0.071 $\mu L\ L^{-1}$; NF + 0.03 = 0.101 $\mu L\ L^{-1}$; NF + 0.06 = 0.125 $\mu L\ L^{-1}$; NF + 0.10 = 0.155 $\mu L\ L^{-1}$. Seasonal 7-h mean O_3 treatments in 1982 were 0.012 $\mu L\ L^{-1}$, 0.031 $\mu L\ L^{-1}$, 0.045 $\mu L\ L^{-1}$, 0.065 $\mu L\ L^{-1}$, 0.077 $\mu L\ L^{-1}$, and 0.092 $\mu L\ L^{-1}$, respectively. Ozone concentrations in O_3-added treatments in 1982 averaged about 60% less than those of 1981 treatments. Other measures

Table 1. Monthly average pan evaporation (mm d^{-1}) at USDA Cotton Experiment Station, Shafter, CA.

Month	1981	1982	Average, 1975–1980
April	5.11	5.20	6.04
May	7.96	8.62	9.21
June	10.19	8.42	10.02
July	10.05	8.04	8.65
August	8.18	6.73	7.23
September	6.70	5.04	6.25
October	3.90	3.74	4.23

Table 2. Seasonal 7-h (0900–1600 h) mean, highest hourly mean, and seasonal mean of the highest daily hourly mean O_3 concentration at Shafter, CA in 1981 and 1982.

	Seasonal 7-h mean		Highest hourly mean		Seasonal mean of daily 1-h means	
Treatment†	1981	1982	1981	1982	1981	1982
	$\mu L\ L^{-1}$					
CF	0.018	0.012	0.036	0.027	0.025	0.016
NF × 0.5	0.045	0.031	0.077	0.057	0.056	0.039
NF	0.071	0.044	0.113	0.081	0.086	0.055
NF (1)	0.101	0.065	0.166	0.142	0.128	0.080
NF (2)	0.125	0.077	0.204	0.185	0.160	0.094
NF (3)	0.155	0.092	0.281	0.209	0.208	0.133
Ambient	0.077	0.047	0.122	0.093	0.089	0.056

† Ozone added treatments in 1981 were (1) NF + 0.03 $\mu L\ L^{-1}$; (2) NF + 0.06 $\mu L\ L^{-1}$; and (3) NF + 0.10 $\mu L\ L^{-1}$. In 1982, O_3 added treatments were (1) NF × 1.3; (2) NF × 1.7; and (3) NF × 2.0 of ambient concentrations.

Table 3. Treatment means† for harvest parameters of normally irrigated (NI) and water-stressed (WS) cotton grown in open-top chambers at Shafter, CA in 1981 and 1982.

Treatment	Seasonal 7-h mean O_3	Bulk wt		Lint wt		Seed wt		Number of open bolls		Weight per boll	
		NI	WS	NI	WS	NI	WS	NI	WS	NI	WS
	μL L⁻¹	g								g	
					1981						
CF	0.018	2110	1193	767	422	1347	838	394	273	5.37	4.41
NF × 0.5	0.045	2009	1402	713	484	1287	929	361	305	5.57	4.61
NF	0.071	1644	1430	611	526	1106	947	328	298	5.04	4.80
NF + 0.03	0.101	1273	1081	457	389	839	720	259	226	4.95	4.79
NF + 0.06	0.125	1281	824	452	296	831	554	246	193	5.19	4.29
NF + 0.10	0.155	878	927	321	333	584	611	185	205	4.59	4.52
AA	0.077	1489	1310	670	510	1128	860	310	237	5.48	5.51
					1982						
CF	0.012	2303	2012	841	729	1398	1268	356	321	6.49	6.25
NF × 0.5	0.031	2314	1861	855	685	1440	1168	354	304	6.53	6.11
NF	0.044	1952	2080	715	702	1221	1295	309	322	6.34	6.46
NF × 1.3	0.065	1309	1452	467	520	831	919	223	255	5.82	5.72
NF × 1.7	0.077	1262	1118	453	409	802	701	230	219	5.51	5.42
NF × 2.0	0.092	790	863	288	311	496	513	148	158	5.35	5.46
AA	0.047	2217	2187	828	823	1368	1346	319	312	6.96	7.01

† Means of four, 1-m row samples from two replicate chambers or plots in 1982; in 1981, means adjusted to two, 2-m samples from two replicate chambers or plots.

of O_3 exposure, including highest 1-h peak and seasonal mean of the highest daily hourly mean, are given in Table 2.

Foliar Injury

Typical O_3 injury symptoms including interveinal chlorotic flecking and purple-brown stippling on adaxial foliar surfaces were noted in all O_3-added treatments in both years. Injury symptoms became increasingly severe as O_3 concentration and duration of exposure increased. Premature senescence and foliar abscission were more pronounced in 1982 than in 1981, producing significantly greater reduction in available photosynthetic leaf surface per plant, particularly in the non-O_3 added treatments. Differences in percent foliar injury between normal and water-stressed plants were not statistically significant in either year. Correlation between percent foliar injury and reduction in lint yield was significant for both 1981 ($r = -0.66$) and 1982 ($r = -0.92$) (Heck et al., 1984).

Yield Responses

Bulk weight, lint weight, seed weight, number of open bolls, and weight per boll of cotton in both normally irrigated and water-stressed treatments were significantly reduced in the high O_3 treatments in both years (Table 3). Numbers of open bolls in the highest O_3 NI treatment were reduced by 53% relative to CF chambers in 1981 and by 58% in 1982. In contrast, comparison of weight per boll from the same treatments gave 14.5% reduction in 1981 and 18% in 1982, indicating that yield reduction was attributable primarily to reduced numbers of open bolls rather than weight per boll. The ratio of lint to seed averaged 0.55 in 1981 and 0.59 in 1982, but did not vary among treatments (Table 3). Plants in WS plots had lower yields and fewer numbers of bolls than in NI plots. These differences were highly significant in 1981, but not in 1982 (Table 4). Analysis of variance of bulk weight indicated a highly significant ($p < 0.001$) O_3 effect in both years and a significant ($p < 0.01$) O_3 × irrigation interaction in 1981. This interaction was not significant in 1982. Position within the chamber was also significant ($p < 0.05$), but position did not significantly interact with O_3 or irrigation. Comparison of AA plots with NF chambers indicated that chamber effects reduced lint yield in NI treatments by 9% in 1981 and 14% in 1982. Water-stressed treatments showed fewer chamber effects, with no difference between AA and NF plots in 1981 and a 7% reduction in NF chamber yield in 1982.

Table 4. Analysis of variance mean squares for yield parameters of 'Acala SJ-2' cotton exposed to O_3 in open-top chambers at Shafter, CA in 1981 and 1982.

Source of variance	df		Bulk wt of bolls		Lint wt	Seed wt	Number of open bolls		Weight per boll	
	1981	1982	1981	1982	1982	1982	1981	1982	1981	1982
Ozone (O_3)	5	5	415 412†	307 782†	42 274†	115 530†	13 283†	14 291†	2 599	33 594**
Irrigation (I)	1	1	829 765†	12 558	1 717	3 528	12 002**	67	35 971**	4 401
O_3 × I	5	5	108 006**	15 296	2 101	5 122	1 773	784	3 711	2 289
Error a	12	12	13 100	20 034	2 785	7 422	736	1 033	1 872	3 906
Position (P)	1	3	67 575*	33 338*	4 276*	12 283**	295	3 259**	10 561*	4 007**
O_3 × P	5	15	22 855	5 715	759	1 696	318	502	1 871	946
I × P	1	3	23 541	5 286	816	2 797	315	1 063	2 670	1 139
O_3 × I × P	5	15	16 374	6 317	1 669	4 205	652	686	892	1 424
Error b	12	36	11 203	8 785	1 261	2 539	542	671	1 921	1 040

*,**,† Significance at the 0.05, 0.01, and 0.001 levels, respectively.

Table 5. Best-fit prediction equations for dose-response of 'Acala SJ-2' cotton grown in open-top chambers at Shafter, CA to seasonal 7-h O_3 concentrations, $\mu L\ L^{-1}$.

Year	Irrigation	Parameter	Equation	R^2
1981	Normal	Bulk wt	$Y = 5\,691 - 22\,571[O_3]$	0.94
		Lint wt	$Y = 2\,059 - 8\,200[O_3]$	0.95
		Seed wt	$Y = 3\,658 - 14\,107[O_3]$	0.93
		Number of open bolls	$Y = 423 - 1\,489[O_3]$	0.95
		Weight per boll	$Y = 5.48 - 31.84[O_3]$	0.54
1981	Water-stressed	Bulk wt	$Y = 2\,971 + 10\,739[O_3] - 102\,300[O_3]^2$	0.63
		lint wt	$Y = 1\,021 + 4\,848[O_3] - 41\,293[O_3]^2$	0.57
		Seed wt	$Y = 3\,000 + 4\,686[O_3] - 57\,116[O_3]^2$	0.71
		Number of open bolls	$Y = 288 + 198[O_3] - 5\,018[O_3]^2$	0.58
		Weight per boll	NS†	
1982	Combined	Bulk wt	$Y = 5\,437 - 418\,556[O_3]^2$	0.79
		Lint wt	$Y = 1\,988 - 154\,532[O_3]^2$	0.79
		Seed wt	$Y = 3\,381 - 256\,557[O_3]^2$	0.81
		Number of open bolls	$Y = 349 - 23\,053[O_3]^2$	0.82
		Weight per boll	$Y = 6.45 - 137.67[O_3]^2$	0.67

† NS = not significant.

The O_3-irrigation interaction was statistically significant in 1981, so data from NI and WS treatments were separated for regression analysis. In 1982 lint and seed yields in NI and WS plots were not statistically different ($p = 0.05$), so data were combined for regression analysis. Yields from AA plots were not included in the regression analysis. Best-fit regression equations for dose-response of cotton yield components to mean seasonal 7-h O_3 concentrations (0900–1600 h) from linear, polynomial, and exponential models are given in Table 5. In 1981, regression between seasonal 7-h O_3 concentration and yield components of NI cotton was linear and highly statistically significant ($p < 0.01$). Each 10% increase in O_3 concentration produced approximately 0.65% decrease in yield. Ambient concentrations of O_3 in NF chambers reduced lint yield 19% relative to yield in CF chambers. Twice ambient O_3 concentration reduced lint yield 45% (Table 6). Yields in WS plots were severely reduced by drought stress and the plants showed relatively little response to O_3 (Fig. 1). In 1982, regressions between yield components and the square of the mean seasonal 7-h O_3 concentration were highly significant ($p < 0.01$) (Table 5). Yields in NF chambers were reduced 15% relative to CF chambers. Twice ambient concentration reduced yield 66% (Table 6). Ambient O_3 concentrations averaged 39% lower in 1982 than in 1981, but yield reductions in NF chambers were comparable (20% in 1981; 15% in 1982) (Fig. 1). No significant reductions in fiber quality were observed in any O_3 treatment in either year.

Table 6. Effects of O_3 on lint production of field-grown 'Acala SJ-2' cotton in open-top chambers at Shafter, CA.†

	1981			1982		
Treatment‡	Ozone§	Lint yield¶	Reduction#	Ozone§	Lint yield¶	Reduction#
	$\mu L\ L^{-1}$	kg ha^{-1}	%	$\mu L\ L^{-1}$	kg ha^{-1}	%
CF	0.018	1870	–	0.012	2050	–
NF × 0.5	0.044	1738	7.1	0.031	2085	–
NF	0.072	1490	20.3	0.044	1744	14.9
NF (1)	0.101	1114	40.4	0.065	1139	44.4
NF (2)	0.125	1102	41.1	0.077	1105	46.1
NF (3)	0.155	781	58.2	0.092	701	65.8

† Plots received recommended rates of irrigation.
‡ Ozone added treatments in 1981 were (1) ambient levels (NF) + 0.03 $\mu L\ L^{-1}$ O_3; (2) NF + 0.06 $\mu L\ L^{-1}$ O_3; and (3) NF + 0.10 $\mu L\ L^{-1}$ O_3. In 1982, O_3-added treatments were (1) NF × 1.3; (2) NF × 1.7; and (3) NF × 2.0.
§ Seasonal 7-h avg (0900–1600 h).
¶ Average of two chambers.
# Relative to CF chambers.

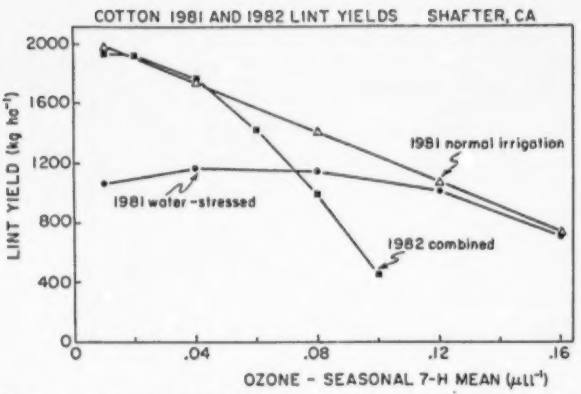

Fig. 1. Comparison of yield losses of normally irrigated (NI) and water stressed (WS) cotton exposed to O_3 in open-top chambers in 1981 and 1982. Yields in NI and WS plots were not statistically different in 1982, so data were combined.

DISCUSSION

Ambient concentrations of O_3 in the San Joaquin Valley of California reduced yield of field-grown 'SJ-2' cotton by 15 to 20% relative to plants grown in CF chambers. These results were similar to those reported by Brewer (Brewer & Ferry, 1974; Brewer, 1979), who observed a 15% reduction in yield of 'SJ-2' cotton in NF chambers. They reported that 'SJ-5,' a variety developed for resistance to *Verticillium* wilt, was less susceptible to O_3 injury and showed no yield reduction in NF chambers. However, other varieties of cotton may be more susceptible to O_3 injury and yield reduction than 'SJ-2.' Heggestad and Christiansen (1982) reported that 'SJ-1,' another California variety similar to 'SJ-2,' was among the most resistant to O_3, compared with varieties developed in other parts of the USA with presumably lower ambient O_3 than the Central Valley of California.

In this study, increasing O_3 concentration had a significantly greater impact on number of bolls than on weight per boll. These results are in agreement with previous greenhouse (Oshima et al., 1979; Heggestad & Christiansen, 1982) and field trials (Brewer, 1979), which also indicated that reduced boll number was the primary determinant of decreased yield. Ozone stress is thus similar to SO_2 (Brisley et al., 1959), nutrition, plant water status, and other environmental factors that are known to determine cotton yield by effects on abscission rates of flower buds and bolls (Stanhill, 1976). Ozone did not affect ratios of lint to seed in these experiments. These results are consistent with those of Oshima et al. (1979), who also reported no effect of O_3

on ratios of boll components. Oshima et al. (1979) observed significant effects of O_3 on partitioning of assimilates between stem and roots. If the reduction in root growth of O_3-exposed cotton reported by Oshima et al. (1979) also occurs in the field, then the potential of O_3-injured cotton to extract available soil moisture could be reduced.

Plant water status had a very significant effect on response of cotton to O_3. In 1981, under conditions of high evaporative demand that normally prevail during summer in the San Joaquin Valley, WS plants frequently wilted during late morning or early afternoon, indicating stomatal closure and reduced rates of gas exchange (Baker, 1965). Yields were severely reduced under these conditions and plants showed comparatively little response to O_3 compared with NI plots (Fig. 1). Plants in NI plots also showed occasional midafternoon wilt in 1981. In 1982, under cooler, more humid growing conditions, pan evaporation was 20% lower than in 1981 and both NI and WS plants were significantly more susceptible to O_3. Under these conditions, stomata in both NI and WS plants remained open during mid and late afternoons, when O_3 concentrations were highest (P. J. Temple, Univ. of California-Riverside, in preparation). Flux of O_3 to internal leaf surfaces may thus have been greater in 1982 than in 1981, despite lower ambient O_3 concentrations in 1982. Evapotranspiration may also influence rates of pollutant uptake by altering internal leaf resistance. High rates of evapotranspiration, such as prevailed in 1981, may reduce pollutant uptake by increasing rates of evaporation from internal leaf surfaces thus slowing rates of inward diffusion (Barton et al., 1980; McLaughlin & Taylor, 1981).

Other factors may have contributed to differences in response of cotton to O_3 in the 2 yr of the study. In 1981, O_3 was added as a square wave function at three prescribed levels above ambient, but in 1982, O_3 was added in proportion to ambient O_3. Since the square wave addition began at 0900 h, when ambient O_3 concentrations were low, the dose of O_3 would be greater under these conditions than in the proportioning system used in 1982. Yet the reduction in cotton yield was greater in 1982. Heagle et al. (1983) compared response of soybean [*Glycine max* (L.) Merr.] to O_3 added to open-top chambers by square-wave and proportioning control systems and found relatively little difference in plant response to the two systems. Ozone-added treatments of cotton began several weeks earlier in 1982 than in 1981, and plants were exposed daily rather than 5 d week^{-1} in 1981; this may have contributed to the large reductions in yield observed at the highest O_3 concentrations in 1982. However, Oshima et al. (1979), in a greenhouse study, initiated O_3 exposures on cotton at 8 and at 42 d of age and found no significant differences in plant response. This suggests that cotton may be equally susceptible to yield reductions whether O_3 exposures begin at the vegetative or square-forming stages of growth.

SUMMARY

Growing conditions in the San Joaquin Valley of California were relatively normal during the summer of 1981; pan evaporation averaged 9.5 mm d^{-1}, daily maximum temperatures frequently exceeded 38°C, and seasonal ambient O_3 concentration averaged 0.077 μL L^{-1} for the period 0900 to 1600 h. Under these conditions, yield of normally irrigated field-grown cotton was reduced 20% in nonfiltered open-top chambers compared with charcoal-filtered chambers. Yield response to O_3 was linear, and double the ambient O_3 concentration reduced yield by 45%. Water-stressed plants had severely reduced yields and showed relatively little response to O_3. In 1982, summer pan evaporation averaged 20% lower than in 1981, maximum temperatures rarely exceeded 33°C, and seasonal 7 h ambient O_3 averaged 0.047 μL L^{-1}. Under these conditions the dose-response of both normally irrigated and water-stressed cotton yield to O_3 was quadratic, decreasing with the square of the O_3 concentration. Yields in nonfiltered chambers averaged 15% lower than in charcoal-filtered chambers and doubling ambient O_3 concentrations reduced yield 66%. The greater relative response to O_3 in 1982 was attributed to the cooler, more humid growing conditions, which increased the susceptibility of cotton to O_3.

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